

# CAAP Annual Report

Date of Report: *October 11, 2015*

Contract Number: *DTPH56-14-H-CAP01*

Prepared for: *DOT*

Project Title: *Patch and Full-Encirclement Repairs for Through-Wall Defects*

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For quarterly period ending: *October 9, 2015*

## **Business and Activity Section**

### **(a) Generated Commitments**

This section is only for the last quarter. There have been no changes to project or project participants at this time.

<b>Supplies Purchased</b>	<b>Cost</b>
Piping and fittings	\$2,334.00
Test Setup Supplies	\$1,024.70

### **(b) Status Update of Past Year Activities**

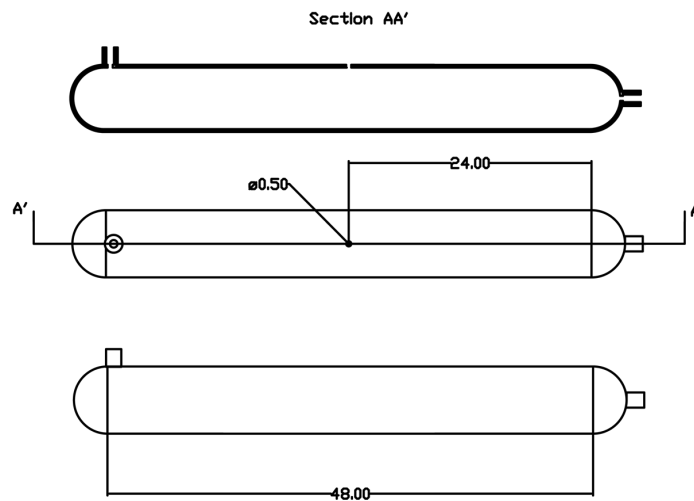
During the first year of this two year CAAP program, we have completed or initiated most of the key technical goals of the program. Specifically, we have accomplished the following research activities

1. Identified graduate student for project and student was accepted by TU – Stephen Theisen
2. Contacted program manager to schedule kick-off meeting.
3. Began finite element studies of repair
4. Sourced material for small and large scale specimens
5. Completed kick-off meeting
6. Fabricated small-scale test pipes.
7. Finalized test plan and scheduled some repair installs.
8. Performed initial testing of a repaired pipe to shakedown testing system and determine factor of safety in ASME PCC-2
9. Supported install of repairs on small-scale specimens.
10. Completed the test instrumentation and control system for the fatigue testing of small-scale specimens.
11. Began fatigue testing of small scale specimens
12. Submitted abstract to the annual conference of the Society for Experimental Mechanics

## Small Scale Test Program

The small-scale test program was the first experimental test that was to be completed for this research project. Each of the participating companies was to repair six pipes with three full encirclement repairs and three patch type repairs. A dimensioned drawing of the test specimen is shown in Figure 1. The specimen was basically a four-foot-long section of 6 in A106B piping with a 0.5 in diameter drilled hole intended to simulate a through-wall defect. The pipe was grit-blasted to a NACE near-white finish prior to the installation of any repairs. One specimen from each of the full-encirclements and the patch repairs was instrumented with strain gages.

A small, custom-designed pressure fatigue testing system was designed around a low-cost, high-pressure water pump. The system was capable of cycling between 0 psi and 1000 psi in approximately 2 seconds. Several safety systems were designed to prevent the accidental over-pressurization of the test specimen. Participating vendors were asked to follow PCC-2 as a minimum when designing the repairs. Additionally, the vendors were asked to maintain the same repair thickness between the patch and the full-encirclement to aid in comparing the performance of the two systems.



**Figure 1: Schematic of the small scale test specimen used in this project. Dimensions are in inches and pipe is a standard ASTM A106B schedule 40 pipe with a 6 in nominal diameter.**



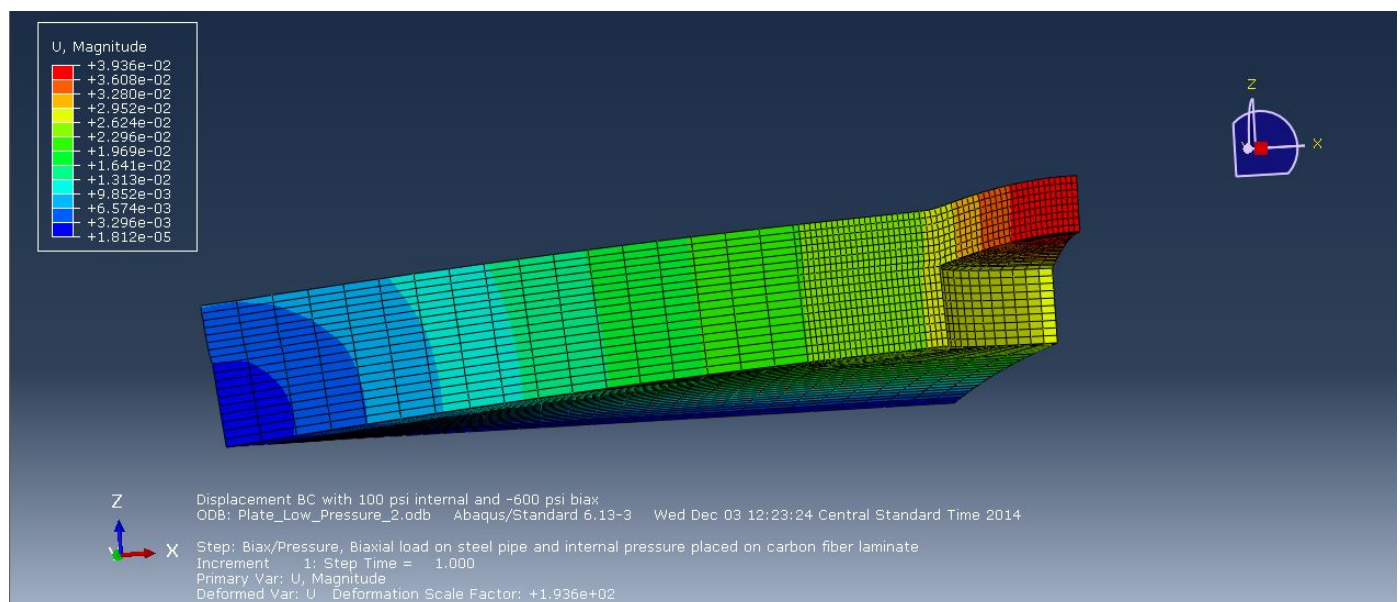
**Figure 2: Picture of full-encirclement repaired pipes in place for fatigue testing.**

At the date of this report, we are currently running fatigue tests on the repaired pipes. We have completed all un-instrumented pipes of one vendor and are nearly complete with the second vendor's pipes. We will

then run the instrumented tests of these two vendors. After completing these tests, we will move to the next vendor's samples and expect to fully complete small-scale fatigue testing by the end of November. After completing the testing of the small scale systems, we will contact the vendors and discuss timing and scheduling for installs on the large pressure vessel. A picture of two of the repaired pipes preparing to undergo fatigue testing is shown in Figure 2.

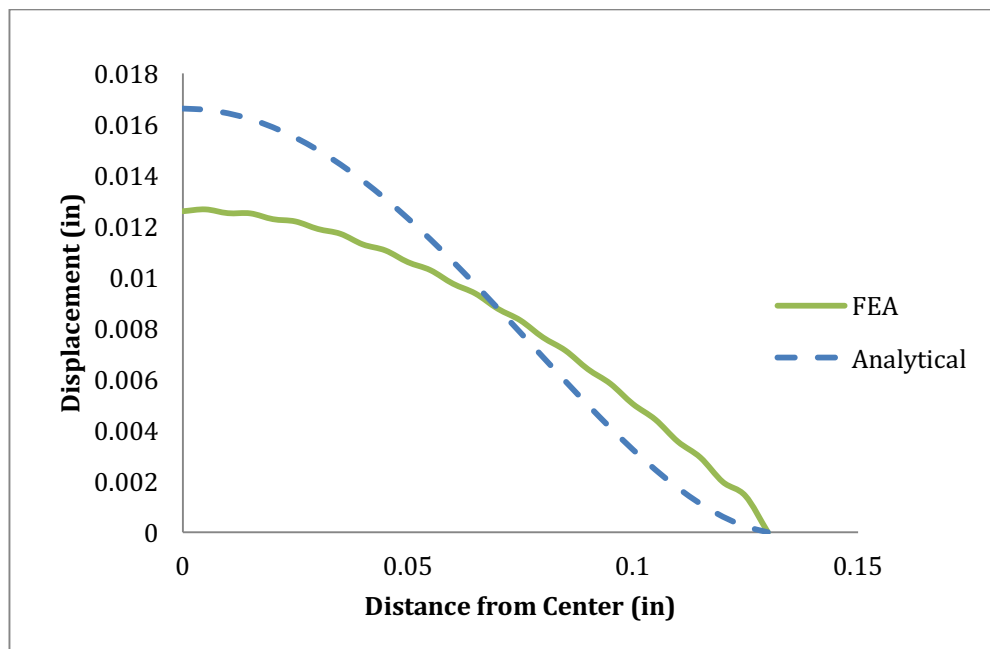
## FEA Studies of Through-wall Defects

During this first year, we have been focusing on developing finite element models of the fracture process for the proposed specimens. We expect that these models will help us understand the performance of the through-wall defects under realistic conditions. The primary goal is to allow us to understand the differences between real-world behavior and the analytical predictions in PCC-2. One of the comparisons that we are attempting to make is to compare the performance of a composite blister on a rigid substrate, as assumed in PCC-2, and a blister on a deformable substrate, as in the real repair. To accomplish this comparison, we are attempting to model a deformable flat plate with a repair. A representative simulation is shown below in Figure 5. A direct comparison between the rigid and deformed plate is somewhat complicated, but using the blister edge as a reference, we can plot the profiles of the blister as shown in Figure 4. As expected, the profile for the deformable substrate exhibits overall lower displacement levels, when compared to a rigid substrate. This is due primarily to the flattening tendency of the biaxial tensile stress state that is present in piping. The added complexity of this deformation makes the volume-change approach for calculating interfacial fracture toughness difficult to use, so we investigated a virtual crack closure techniques (VCCT) to help understand the crack tip stress intensity in this more realistic loading scenario.



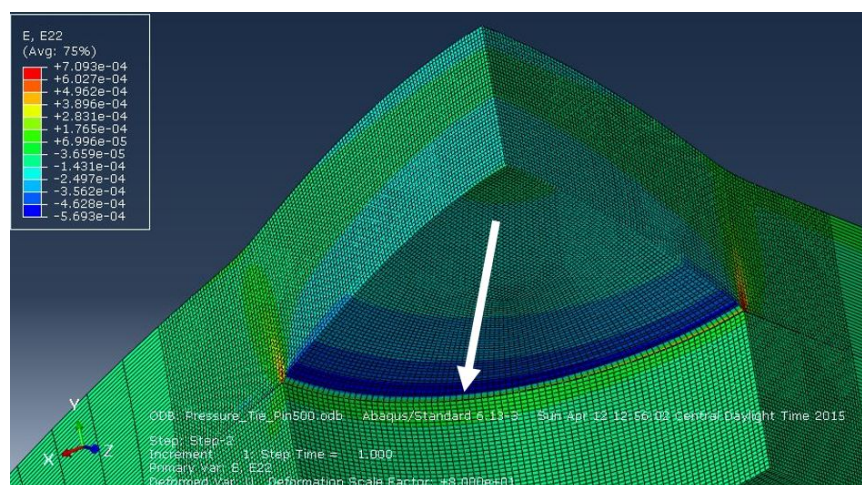
**Figure 3: FEA results of a simulation of a deformable plate with applied repair. Contours represent displacement.**

At the moment, we have suspended the use of VCCT in favor of a simpler strain analysis at the interface. The expectation is that by understanding the stress-strain state of the repair near the interface of the steel/composite at the edge of the hole, we can directly compare the behavior of the patch and full-encirclement repairs. Eventually, the extraction of a fracture-energy parameter will be needed to help design, but if this proves too complicated a strain-based comparison should prove insightful.

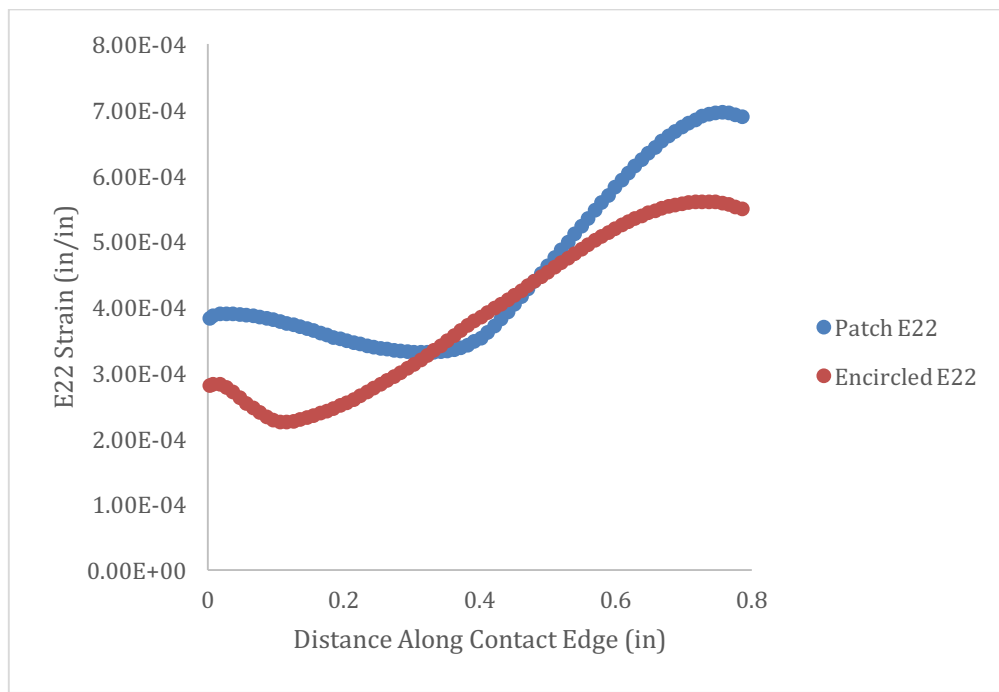


**Figure 4: Comparison of a FEA-predicted blister profile and an analytical profile.**

As discussed above, we have transitioned to a strain-based analysis of the defect and Figure 5 shows a FEA simulation result with a white arrow indicating the interface between the substrate pipe and the composite repair. Strains in the repair were extracted along this line as a stand in for opening forces that tend to drive crack propagation. Figure 7 shows the FEA predicted strains along this interface for a patch and a full encirclement repair. From this data we can see that the patch repair has larger maximum strains when compared to the patch repair. The average strain level is also higher for patch repairs when compared to full encirclements. Based on the deformation of a full-encirclement repair compared to a patch repair, the increase in strain is likely due to increased bending deformation of the base pipe. Increased deformation tends to pull the substrate away from the repair, likely causing the observed increase in opening strains. This result tends to indicate that a patch repair will have relatively poorer performance when compared to the full-encirclement. This has yet to be confirmed with experimental data.



**Figure 5: FEA results of a simulation of a composite repair indicating interface that we are currently studying.**



**Figure 6: Comparison of a FEA-predicted opening strain (e22) at the location indicated in Figure 5.**

One of the interesting features of the extracted strains is the peak in the strains shown in Figure 6. We believe that this is due to mesh distortion and is not actually representative of the real stress state. A complete mesh quality and convergence study is underway and we expect that this should clarify if the strain “peaks” are due to anisotropy of the repair or simply distorted elements.

In addition to the investigation of the interfacial opening strains and repair deformation profiles, we have also investigated the impact of repair extent of interfacial shear stress. There are several competing opinions regarding the calculations of the length of the repairs as presented in the ASME PCC2 standard the relevant ISO standard. We performed several simulations where we varied the length of the repair and investigated the in-plane shear strain at the interface of the composite and the substrate.

As seen in previous FEA studies the strain in the patch specimen is actually slightly lower than that of the full-encirclement repairs. In general increasing length of repair reduced the maximum interfacial shear strains rather significantly. This result does tend to lend support to the strain-based calculation of extent of repair as provided in PCC2 and ISO. We are working to understand exactly how critical this length is in ensuring a safe, reliable repair. It is important to note that, even at the shortest lengths, the shear strain values are very low with respect to the maximum failure strain of most composites (0.01 in/in).

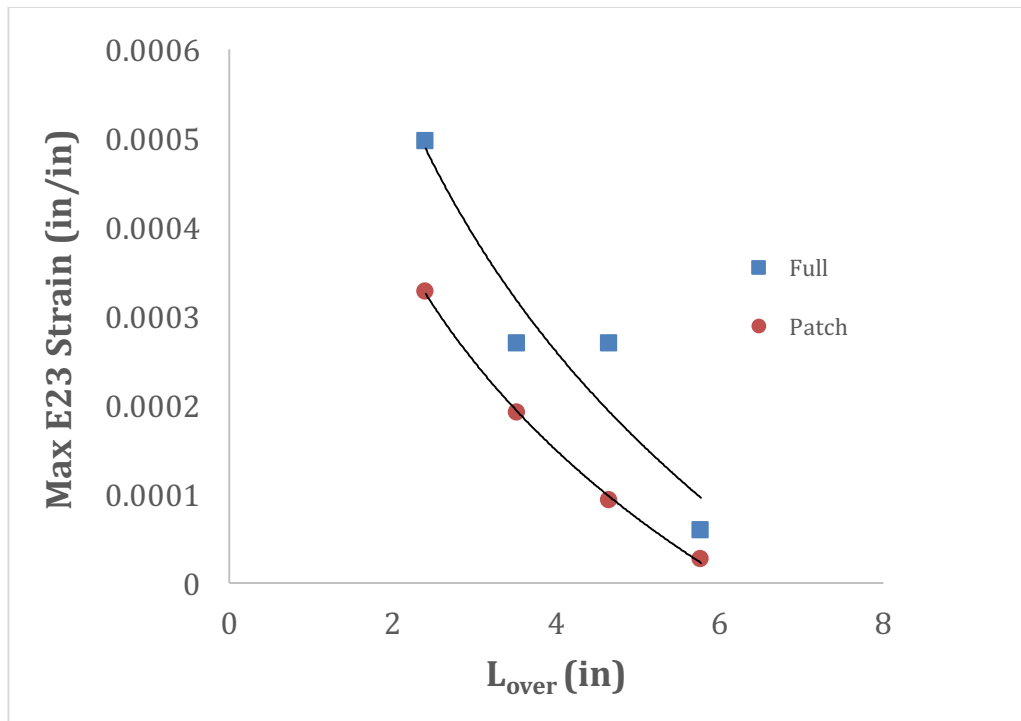


Figure 7: Comparison of interfacial shear strain as a function of extent of repair along the axis of the pressure vessel.

We have also begun modeling the large scale vessel for comparison with future experimental results and to understand the differences between the two size scales. We had initially expected to have some results by this report, but the experimental testing has proven to require observation limiting available student time. As we begin to complete the small-scale testing program we will return to the FEA studies and complete the computational analysis of the differences between the small and large scale specimens.

### Other Accomplishments

We have submitted an abstract to Society of Experimental Mechanics to present the current results of this study.

### (c) Description of any Problems/Challenges

During this past quarter there were no significant challenges. As in last quarter, we are working to make sure that the two patches related programs are moving together and are attempting to limit any slow-downs with respect to testing conflicts for these two test programs.

### (d) Planned Activities for the Next Quarter –

Planned activities for the next quarter include the following

1. Continue fatigue testing of small scale repairs.
2. Begin fabrication of large-scale test vessel.
3. Finalize FEA studies of small-scale specimens.